

# Interstellar Dust in the Solar System

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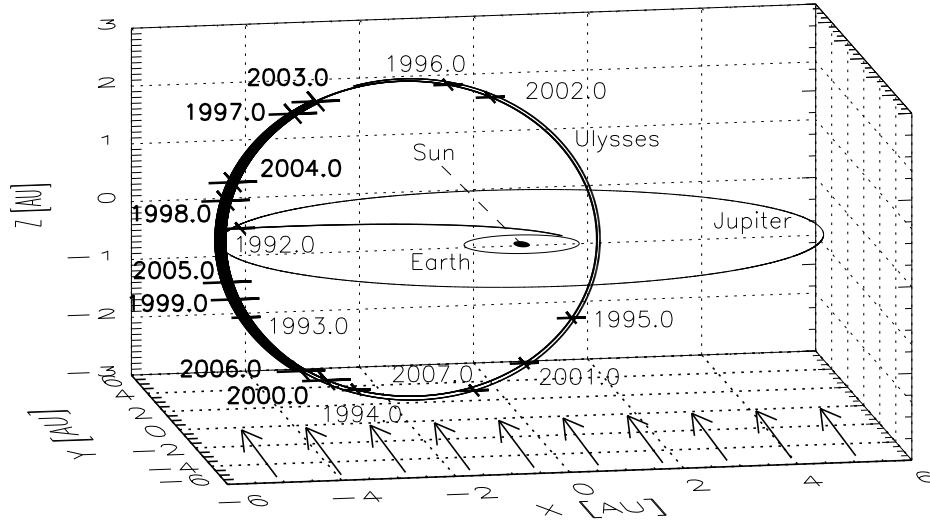
**Abstract.** The Ulysses spacecraft has been orbiting the Sun on a highly inclined ellipse almost perpendicular to the ecliptic plane (inclination  $79^\circ$ , perihelion distance 1.3 AU, aphelion distance 5.4 AU) since it encountered Jupiter in 1992. The in-situ dust detector on board continuously measured interstellar dust grains with masses up to  $10^{-13}$  kg, penetrating deep into the solar system. The flow direction is close to the mean apex of the Sun's motion through the solar system and the grains act as tracers of the physical conditions in the local interstellar cloud (LIC). While Ulysses monitored the interstellar dust stream at high ecliptic latitudes between 3 and 5 AU, interstellar impactors were also measured with the in-situ dust detectors on board Cassini, Galileo and Helios, covering a heliocentric distance range between 0.3 and 3 AU in the ecliptic plane. The interstellar dust stream in the inner solar system is altered by the solar radiation pressure force, gravitational focussing and interaction of charged grains with the time varying interplanetary magnetic field. We review the results from in-situ interstellar dust measurements in the solar system and present Ulysses' latest interstellar dust data. These data indicate a  $30^\circ$  shift in the impact direction of interstellar grains w.r.t. the interstellar helium flow direction, the reason of which is presently unknown.

**Keywords:** dust, interstellar dust, heliosphere, interstellar matter

## 1. Introduction

One of the most important results of the Ulysses mission is the identification and characterization of a wide range of interstellar phenomena inside the solar system. A surprise was the identification of interstellar dust grains sweeping through the solar system (Grün et al. (1993)). Before this discovery it was believed that interstellar grains are prevented from reaching the planetary region by electromagnetic interaction with the solar wind magnetic field. The interplanetary zodiacal dust flux was thought to dominate the near-ecliptic planetary region while at high ecliptic latitudes only a very low flux of dust released from long-period comets should be present. Therefore, the characterization of the interplanetary dust cloud was the prime goal of the Ulysses dust investigation (Grün et al. (1992)).

Ulysses was launched in October 1990. A swing-by manoeuvre at Jupiter in February 1992 rotated its orbital plane  $79^\circ$  relative to the ecliptic plane (with a six-year orbital period and aphelion distance at 5.4 AU; Figure 1). Subsequent aphelion passages occurred in April 1998 and in June 2004. A second Jupiter flyby occurred in February 2004. The best conditions for detection of interstellar impactors are



*Figure 1.* The trajectory of Ulysses in ecliptic coordinates. The Sun is in the centre. The orbits of Earth and Jupiter indicate the ecliptic plane. Ulysses' initial trajectory was in the ecliptic plane. Since Jupiter flyby in early 1992 the orbit has been almost perpendicular to the ecliptic plane ( $79^\circ$  inclination). Crosses mark the spacecraft position at the beginning of each year. The 1997 to 1999 and 2003 to 2005 parts of the trajectory are shown as a thick line. Vernal equinox is to the right (positive  $x$  axis) and the flow direction of the interstellar grains (coincident with the interstellar helium flow) is indicated by arrows.

in the outer solar system beyond 3 AU at high ecliptic latitudes and far away from Jupiter where impact rates of interplanetary grains or jovian stream particles are comparatively small. Nevertheless, Ulysses has continuously monitored the interstellar dust flux in the heliosphere since 1992.

We briefly review the results from in-situ interstellar dust measurements with the Ulysses and other space-borne dust detectors in Section 2. In Section 3 we present the interstellar dust measurements from the Ulysses' 3<sup>rd</sup> passage through the outer heliosphere, and Section 4 is a brief discussion of our results.

## 2. Interstellar dust measurements in the heliosphere

Interstellar dust particles originating from the Local Interstellar Cloud (LIC) move on hyperbolic trajectories through the solar system and approach Ulysses predominantly from the direction opposite to the expected impact direction of interplanetary grains. On average, their impact velocities exceed the local solar system escape velocity, even if radiation pressure effects are neglected (Grün et al. (1994)). The grain motion through the solar system was found to be parallel to the flow of neutral interstellar hydrogen and helium gas, both gas and dust travelling with a speed of

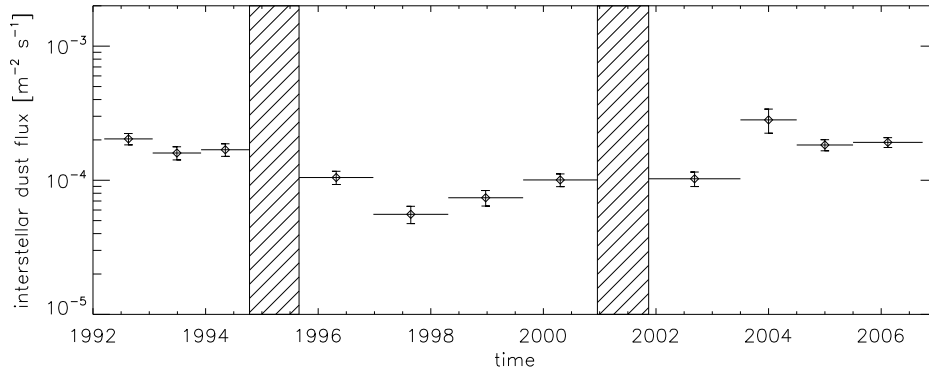
$26 \text{ km s}^{-1}$  (Grün et al. (1994); Baguhl et al. (1995); Witte et al. (1996); Frisch et al. (1999)). The interstellar dust flow persisted at high latitudes above and below the ecliptic plane and even over the poles of the Sun, whereas interplanetary dust was strongly depleted at high ecliptic latitudes.

Later measurements with the Galileo dust detector in the ecliptic plane confirmed the Ulysses results: beyond about 3 AU the interstellar dust flux exceeds the flux of micron-sized interplanetary grains. Furthermore, interstellar dust is ubiquitous in the solar system: dust measurements between 0.3 and 3 AU in the ecliptic plane exist also from Helios, Galileo and Cassini. This data shows evidence for distance-dependent alteration of the interstellar dust stream caused by radiation pressure, gravitational focussing and electromagnetic interaction with the time-varying interplanetary magnetic field which also depends on grain size (Altobelli et al. (2003); Altobelli et al. (2005b); Altobelli et al. (2005a); Mann & Kimura (2000); Landgraf (2000); Czechowski & Mann (2003)). As a result, the size distribution and fluxes of grains measured inside the heliosphere are strongly modified (Landgraf et al. (1999a); Landgraf et al. (2003)).

Interstellar grains observed with the spacecraft detectors range from  $10^{-18} \text{ kg}$  to above  $10^{-13} \text{ kg}$ . If we compare the mass distribution of these interstellar impactors detected in-situ with the dust mass distribution derived from astronomical observations, we find that the in-situ measurements overlap only with the largest masses observed by remote sensing. It indicates that the intrinsic size distribution of interstellar grains in the LIC extends to grain sizes larger than those detectable by astronomical observations (Frisch et al. (1999); Frisch & Slavin (2003); Landgraf et al. (2000); Grün & Landgraf (2000)). Even bigger interstellar grains (above  $10^{-10} \text{ kg}$ ) are observed as radar meteors entering the Earth's atmosphere (Taylor et al. (1996); Baggaley & Neslušan (2002)). The flow direction of these larger grains varies over a much wider angular range than that of small particles measured by the in-situ detectors.

The total grain mass detected in-situ by Ulysses, which includes bigger grains in the LIC than those detectable with astronomical techniques, led to the conclusion that the LIC gas is enhanced with the refractory elements (e.g. Fe, Mg, Mn) that would ordinarily dominate the mass of interstellar dust grains. Earlier investigations indicated an enhancement of the dust-to-gas mass ratio in the LIC by up to a factor of five (Frisch et al. (1999)). Recent reanalysis with improved solar heavy element abundances and an updated value for the sensitive area of the Ulysses dust detector (Altobelli et al. (2004)) brought this enhancement down to a factor of two (Frisch & Slavin (2003))(Slavin & Frisch, this volume).

In addition to the distribution of grain masses, the instrument has monitored the flux of interstellar dust particles through the heliosphere since Ulysses left the ecliptic plane in 1992 (Figure 2). In mid 1996, a drop of the interstellar dust flux from initially  $1.5 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$  to  $0.5 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1}$  occurred (Landgraf et al. (1999b)). Since early 2000, Ulysses has detected interstellar dust flux levels above  $10^{-4} \text{ m}^{-2} \text{ s}^{-1}$  again. The drop in 1996 was explained by increased filtering of small



*Figure 2.* Interstellar dust flux measured by Ulysses. The horizontal lines indicate the length of the time intervals, and the vertical bars of the data points represent the  $1\sigma$  uncertainty due to small number statistics. The dashed regions in 1995 and 2001 show the periods of Ulysses' perihelion passages where the distinction of interstellar dust from interplanetary impactors is difficult. Furthermore, in 2003 and 2004 a possible contamination by jovian dust stream particles around Jupiter flyby, which occurred in February 2004, may lead to an erroneously enhanced interstellar flux. Dust streams identified in the Ulysses data set were removed by ignoring the time interval when a dust stream occurred.

grains by the solar wind driven magnetic field during solar minimum conditions (Landgraf et al. (2000); Landgraf (2000)). The filtration caused a deficiency of detected interstellar grains with sizes below  $0.2\ \mu\text{m}$  (Grün et al. (1994)). An additional filtration by solar radiation pressure, which was found to be effective at heliocentric distances below 4 AU, deflects grains with sizes of  $0.4\ \mu\text{m}$  (Landgraf et al. (1999a)).

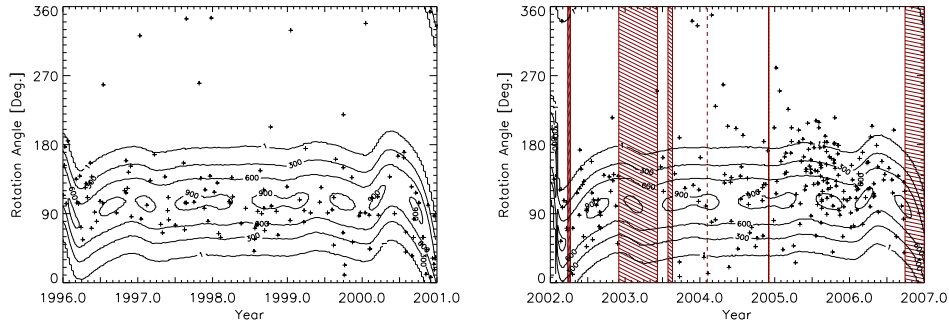
Modelling the dynamics of the electrically charged dust grains in the heliosphere can give us information about the Local Interstellar Cloud (LIC) where the particles originate from. In the time interval 2001 to 2003 the interstellar dust flux stayed relatively constant, in agreement with improved models (Landgraf et al. (2003)). The dominant contribution to the flux comes from grains with a charge to mass ratio  $q/m = 0.59\ \text{C kg}^{-1}$  and a radiation pressure efficiency of  $\beta = 1.1$  which – in the simulation – corresponds to a grain radius of  $0.3\ \mu\text{m}$  (assuming spherical grains). The models assume a constant dust concentration in the LIC and give a good fit to the dust fluxes measured between end-1992 and end-2003. The fact that the models fit the observed variations implies that the dust phase of the LIC is homogeneously distributed over length scales of at least 50 AU which is the distance inside the LIC traversed by the Sun during this time period. This result, however, needs to be reexamined in light of Ulysses's most recent measurements obtained during the spacecraft's 3<sup>rd</sup> passage through the outer solar system.

### 3. Ulysses's 3<sup>rd</sup> passage through the outer solar system

From 2002 to 2006 Ulysses made its 3<sup>rd</sup> passage through the outer heliosphere (aphelion passage occurred in June 2004 at a heliocentric distance of 5.4 AU), providing again good conditions for measuring interstellar dust. In February 2004, however, the spacecraft had its second Jupiter flyby at a closest approach distance 0.8 AU which also allowed for good measurement conditions for the dust streams emanating from the jovian system (Grün et al. (1993); Krüger et al. (2006)). A total of 28 streams were detected, more than twice the number of detections from Ulysses' first Jupiter flyby in 1992: the first stream was recorded in November 2002 when Ulysses was still 3.4 AU away from Jupiter, and the last stream in mid-2005 at more than 4 AU jovicentric distance.

In the outer solar system and at high ecliptic latitudes the interstellar impactors can usually be identified by their impact direction: they approach from a retrograde direction while the majority of interplanetary grains move on prograde heliocentric orbits. During most of the time in the 2002 to 2005 interval, however, the jovian dust streams approached from roughly the same direction (Krüger & Grün (2007)), so that identification of interstellar grains by their impact direction alone was not possible. On the other hand, the measured impact charge distribution showed that the majority of grains with impact charges above  $Q_I = 2 \times 10^{-13}$  C are of interstellar origin while most jovian stream particles have impact charges below this limit. We therefore use this limit to separate both populations of impactors. Contamination by jovian stream particles, however, cannot entirely be excluded this way, and in particular the fluxes attributed to interstellar grains in 2004 – when the instrument detected the most intensive jovian dust streams (Krüger et al. (2006)) – may be contaminated by jovian impactors. Hence, the data point in Figure 2 showing an elevated interstellar flux in 2004 has to be taken with caution. On the other hand, in mid-2005 dust stream detections ceased, and in the later data the contribution by jovian stream particles should be negligible.

Figure 3 shows the impact directions of grains with impact charges  $Q_I \geq 2 \times 10^{-13}$  C for two different time intervals. The intervals were chosen such that Ulysses was traversing approximately the same region of the outer solar system during both periods. Contour lines show the effective dust sensor area for particles approaching from the upstream direction of interstellar helium (Witte et al. (1996)), implying that the detection conditions for interstellar dust were very similar in both intervals. The approach directions of the majority of grains are consistent with the upstream direction of the interstellar helium flow. This is particularly evident in the earlier time interval 1996 to 2000 (*left panel* in Figure 3). It should be noted that in this interval Jupiter and Ulysses were on opposite sides of the solar system, separated by more than 10 AU, so that contributions by jovian stream particles can be excluded. The distribution of the measured rotation angles is also shown in Figure 4. In the 1997 to 1999 interval the average impact direction of the interstellar grains was at rotation angles of about  $95^\circ$ .



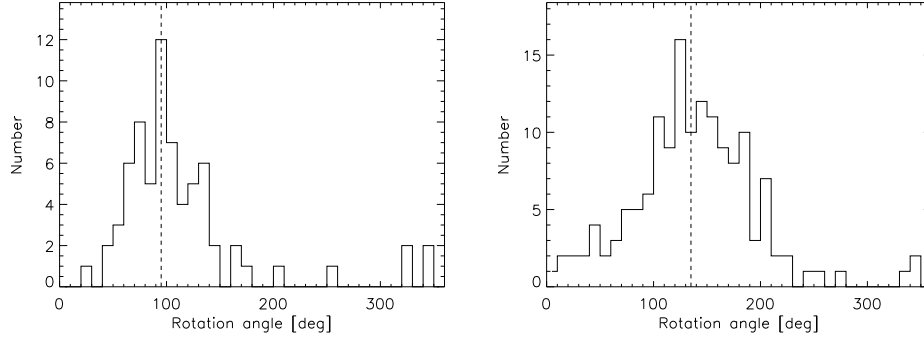
*Figure 3.* Impact direction (i.e. spacecraft rotation angle at dust particle impact) of interstellar grains measured with Ulysses in two time intervals. *Left:* 1 January 1996 to 31 December 2000; *right:* 1 January 2002 to 31 December 2006. Ecliptic north is close to  $0^\circ$ ; impact charges  $Q_I \geq 2 \times 10^{-13}$  C. Each cross indicates an individual impact. Contour lines show the effective sensor area for particles approaching from the upstream direction of interstellar helium. In the right panel, a vertical dashed line shows Jupiter closest approach on 5 February 2004, five shaded areas indicate periods when the dust instrument was switched off.

The interstellar impactors were still concentrated towards the interstellar helium flow direction in 2003 and 2004 (*right panel* in Figure 3) although the distribution of the measured rotation angles was somewhat wider. Later, in 2005, the impact directions were significantly shifted from the helium flow. This is also evident in the *right panel* of Figure 4: the mean rotation angle of the impactors is at  $135^\circ$  rotation angle. Taking into account that the detection geometry has slightly changed between the two time intervals, this implies that the interstellar dust flow has shifted by at least  $30^\circ$  in southward direction, away from the ecliptic plane. The wider distribution of impact directions is also evident.

#### 4. Discussion

The dust measurements from Ulysses' 3<sup>rd</sup> passage through the outer solar system imply an at least  $30^\circ$  shift in the approach direction of interstellar dust grains. The reason for this shift remains mysterious. Whether it is connected to a secondary stream of interstellar neutral atoms shifted from the main neutral gas flow (Collier et al. (2004)) is presently unclear. However, given that the neutral gas stream is shifted along the ecliptic plane while the shift in the dust flow is offset from the ecliptic, a connection between both phenomena seems unlikely.

Even though Ulysses' position in the heliosphere and the dust detection conditions were very similar during both time intervals considered here, the configurations of the solar wind driven interplanetary magnetic field (IMF) which affected the grain dynamics were vastly different. One has to take into account that the interstellar grains need approximately twenty years to travel from the heliospheric



*Figure 4.* Distribution of measured impact directions (i.e. spacecraft rotation angle at dust particle impact) of interstellar impactors for two time intervals. *Left:* 1 January 1997 to 31 December 1999; *right:* 1 January 2003 to 31 December 2005. In the earlier time interval the maximum of the distribution is at a rotation angle of  $95^\circ$  very close to the value expected from the interstellar helium flow. In the second interval the maximum is at  $135^\circ$ .

boundary to the inner solar system where they are detected by Ulysses. Thus, the effect of the IMF on the grain dynamics is the accumulated effect caused by the interaction with the IMF over several years. Hence, in the earlier time interval (1997-1999) the grains had a recent dynamic history dominated by solar minimum conditions (Landgraf (2000)), while the grains detected during the second interval (2002-2005) had a recent history dominated by the much more disturbed solar maximum conditions of the IMF. This latter configuration may have a strong influence on the dust dynamics in the inner heliosphere but it is not modeled in detail in the presently existing models. It may particularly affect small grains which are most sensitive to the electromagnetic interaction. One would expect a size-dependent shift in the grain impact direction which, however, is not evident in the data. Whether these phenomena cause the observed shift in the approach direction of the interstellar dust grains will be the subject of future investigations.

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